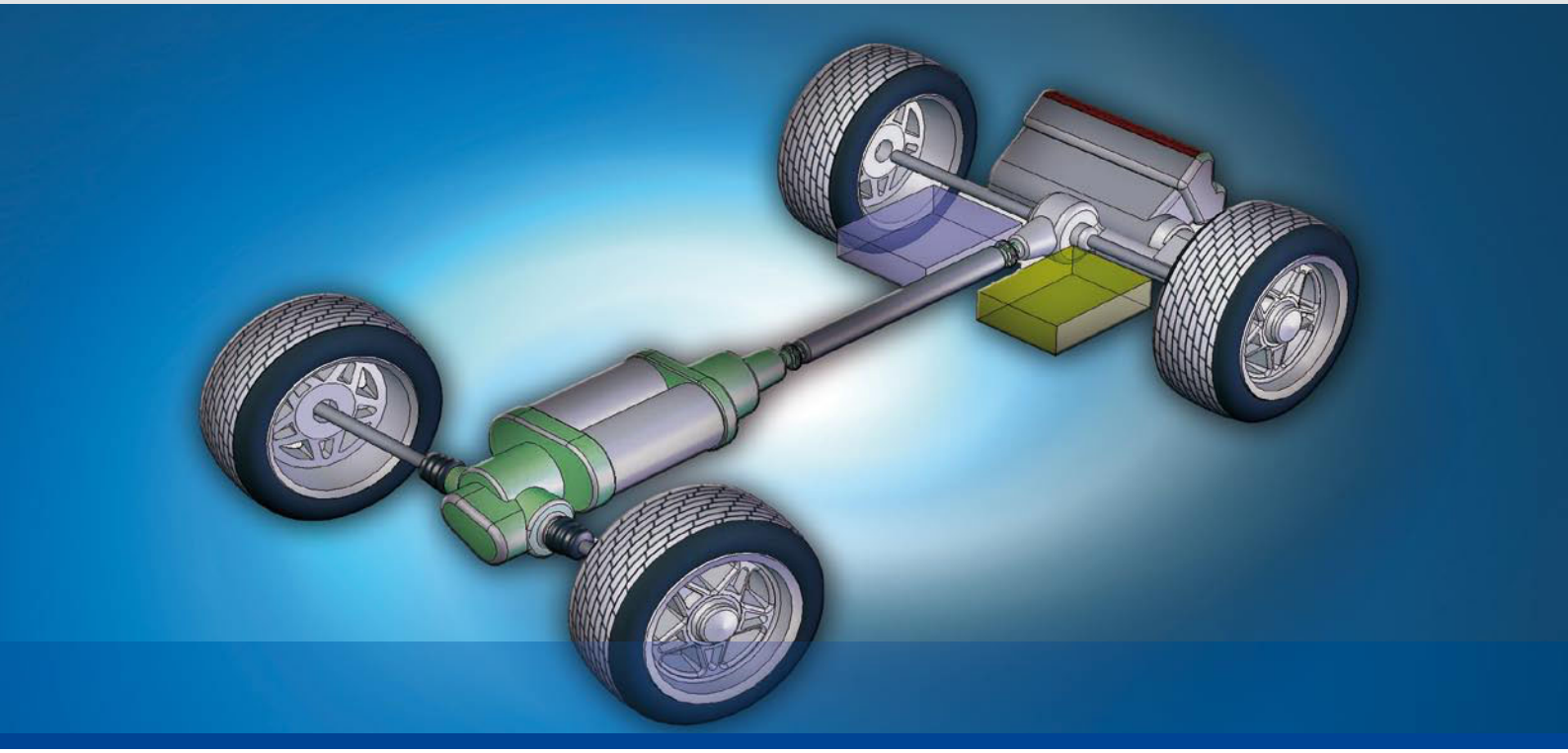

1 The Fundamentals

Figure 1 shows the energy relationship between a surge power unit designed to recycle a vehicle's surplus kinetic energy and its host vehicle. The key to urban fuel consumption is conservation of a vehicle's kinetic energy by recovering as much as practical during braking, storing it temporarily and then using the stored kinetic energy in preference to any other energy source in accelerating the vehicle back up to speed. The more efficient the process of recycling the vehicle's kinetic energy becomes, the less critical the weight of the vehicle is to the net energy required to move the vehicle, provided the surge power unit is sufficiently powerful to provide adequate acceleration. Because kinetic energy recycling is needed in fuel cell vehicles and zero-emissions vehicles as well as in hybrids, the term hybrid drive is inappropriate as a label for the heart of the system if a common platform is required, so the term Surge Power Unit (SPU) is preferable. Therefore the term Kinetic Energy Recovery System (Kers) is not used because the SPU is expected to do a lot more than just support regenerative braking.

In a conventionally powered car, the principal tasks of the engine are to accelerate the vehicle and then to replace the losses, mainly aerodynamic losses when the car is cruising at speed. To slow down rapidly, most of the vehicle's expensively acquired kinetic energy must be thrown away as heat by the friction brakes. Current hybrid vehicles transform some of their kinetic energy into electrical energy by using a generator to assist braking, thus reducing the amount of energy the brakes need to throw away. The electricity generated during braking is then stored temporarily by transforming it again into chemical energy in a battery. On acceleration, this complex and lossy set of processes is reversed, to provide some of the kinetic energy needed to get back up to speed, and the amount of fuel used in urban driving is consequently reduced. However, although each of the four transformations required in a full energy recycle of braking and accelerating may be relatively efficient, the losses incurred during each transformation are not just additive, they multiply together to give a disappointing result. The net effect is that most current hybrids rarely achieve as much as 35 % efficiency in a full regenerative braking cycle. An additional problem is the low power output of the batteries fitted to most current hybrids. Only weak acceleration can be achieved before the engine must fire up to provide the rest of the power required.

It is a fundamental of physics, touched on in the Second Law of Thermodynamics and confirmed in practise throughout engineering, that changing energy from one form to another inherently results in significant losses. In contrast, transferring or transmitting energy in the same form, done well, can result in very low losses. This is the basic argument for using kinetic energy storage (that is flywheels or high-speed rotors) to hold temporarily the kinetic energy recovered during braking. It also argues for an all-mechanical solution to the requirement for an infinitely variable transmission (IVT) to link the rotors to the driving wheels, **Figure 2**. The alternative of using a flywheel battery connected to an electric traction motor still involves four electro-mechanical transformations which, although likely to be collectively more efficient than the four transformations required when batteries or capacitors are used, are inherently incapable of being as efficient, net, as an all-mechanical solution.

Figure 3 illustrates how a few tens of kilograms of rotors revolving at high-speed can store as much energy as a typical car travelling at cruising speed, courtesy of the square law governing the kinetic energy of a moving body. The objective is for kinetic energy to move, with minimal losses, to and fro between host vehicle and SPU, as vehicle speed rises and falls.

The Vehicle as Kinetic Energy System

The principal task of the engine is to convert chemical energy into kinetic energy and then replace the various losses. So a car, which exists primarily to provide personal mobility, can be regarded technically as a kinetic energy system, above all else. This examination by Hy Kinesys and the City University of London (UK) identifies a more efficient way to provide regenerative braking and finds a more cost-effective way to provide acceleration without requiring the engine to provide most of the accelerative power.

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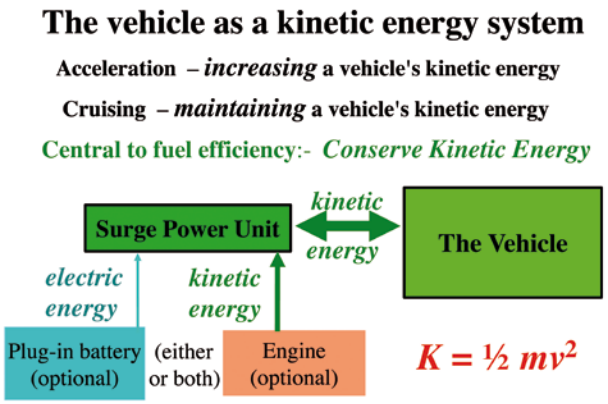
2 Beyond Formula 1

Formula 1 (F1) will introduce fuel-only hybrids next year. A simple Kers based on kinetic energy storage and an all-mechanical Continuously Variable Transmission would seem optimal on first sight of the regulations, and several teams may take this approach. But road cars are likely to get kinetic surge power even earlier. There are fewer regulatory limitations on road car designs than on F1 race cars but there are also more demanding real requirements, the four most notable being cost, durability, efficiency and the need to integrate electric and engine power in a plug-in hybrid. The last is a challenge unlikely to reach F1 for at least a decade, if ever, given the current and projected levels of battery specific energy and the very high energy-flow requirements of racing. Maybe reason will begin to prevail when the next generation of F1 engines are introduced in 2011 or 2013, and the F1 regulations will begin to encourage road-relevant solutions in racing [1].

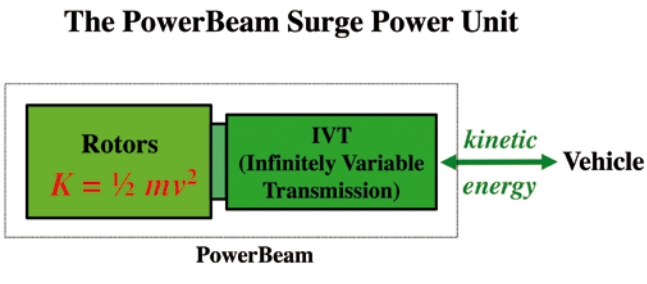
Figure 1 illustrates the high-level relationships between a road vehicle, its SPU, its engine and the battery optionally fitted to extend AER. Kinetic energy flows to and fro between the SPU and the vehicle during braking. The engine may add kinetic energy as required by the Power Train Controller (not shown) to the combined system of vehicle and SPU in order to make up losses, take the vehicle speed beyond normal levels and also to supply the initial energy required to bring the total kinetic energy in the vehicle/SPU combination up to the required operating level. The battery, if fitted, will contribute similarly and preferably, until it reaches its minimum state-of-charge (SOC) and hopefully has delivered the promised AER. In all applications except a fuel-only hybrid, the presence of an electrical energy source will require an electric motor capable of transforming electrical energy into kinetic energy at the average rate required to overcome the total average losses from aerodynamic drag, rolling resistance, etc.

It seems preferable in most applications using batteries for temporary energy storage to allow the engine to support the



Kinetic energy moves from the vehicle to the SPU during braking, and back again on accelerating. The main task of the engine or battery is replacing the losses in the kinetic energy system.

Figure 1: The relationship between a vehicle, its surge power unit and other key components



Kinetic energy moves from the vehicle to the SPU during braking, and back again to the vehicle on accelerating. The engine and/or the battery replenish the losses in the kinetic energy system. They are both 'Range Extenders'.

Figure 2: The Powerbeam surge power unit uses rotors for kinetic energy storage

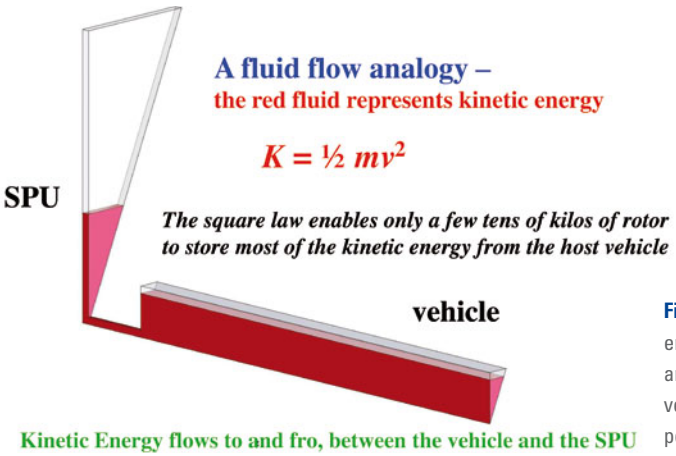

A fluid flow analogy –
the red fluid represents kinetic energy
$K = ½ mv^2$
SPU
The square law enables only a few tens of kilos of rotor
to store most of the kinetic energy from the host vehicle
vehicle
Kinetic Energy flows to and fro, between the vehicle and the SPU

Figure 3: Kinetic energy flows to and fro between vehicle and surge power unit rotors

battery even when the battery is well above its minimum SOC, rather than require that the battery discharge rates and motor power ratings must be sufficient to deal with all eventualities until the battery has discharged to its limit and the engine must start. Most vehicle owners will be motivated to opt for a plug-in battery by a desire to minimise total costs over the full life of the vehicle, not by a specific desire to maximise engine-off miles. Where electricity can be renewably sourced or generated in fusion plants (eventually), there is a strong societal argument to maximise the use of such electricity, but this does not usually translate directly into a requirement to maximise each vehicle's AER. Using an SPU to buffer the battery and engine power demands allows more cost-effective implementations of both, and more efficient use of both by reducing the energy required from both the engine and the plug-in battery.

3 Electro-Mechanical IVT

The requirement to combine the two-way flow of kinetic energy between the vehicle and the rotor(s) of a kinetic energy storage system with the one-way transformation of electrical energy from a plug-in battery into kinetic energy has led to a novel and patented design of electro-mechanical IVT, **Figure 4** [2]. It achieves higher efficiency than a flywheel-battery solution by passing approximately half its energy to and from the high-speed rotors via a single-stage planetary gear set, at an efficiency in excess of 95 % over most of the speed range. The other half of the energy passes via two motor/generators, the one on the low-speed shaft also acting as the motor to deliver the energy from the plug-in battery, if fitted. This brings the electro-mechanical IVT into cost-contention with the all-mechanical solution when the latter has to be paired with an electric motor to provide for plug-in power. **Figure 5** shows the physical relationship between the two counter-rotating rotors and associated IVT of a Powerbeam suitable for mounting under the hood of a rear-wheel-drive, rear-engined vehicle.

The first electro-mechanical IVT embodying the concepts outlined above is expected to be demonstrated initially in a large saloon car, by mid-2009. This first version of the SPU will add some 104 kW to the 194 kW of the conventional version of the host, more than twice the net additional power of any current hybrid car. It will also feature over-boost, which is expected to add a further 150 kW for a few seconds. This should raise its practical levels of acceleration to those of a typical turbocharged 5.5 l V 8 engine, while providing the equivalent of 2 l diesel fuel economy in the city, on petrol, and performing as a powerful electric vehicle when a plug-in battery is fitted.

4 Current Hybrids

A typical premium model range in a few years time will probably start with a conventional internal combustion engine with merely adequate performance, supported by a more expensive hybrid version with a similar engine but also a powerful SPU to provide V8 levels of acceleration plus improved fuel consumption. To reduce fuel consumption further, most manufacturers may well offer the option of adding plug-in battery modules, probably in increments of some 16 km to 20 km of AER. Rather than forcing all hybrid customers to pay for a minimum of 65 km of AER as some are proposing, this modular approach will allow each car to start life with a cost-optimal AER, which could then be adjusted, with changing use and falling battery prices, over the life of the vehicle. There is also a strategic issue here, for those governments considering battery subsidies. If large traction batteries are going to be a scarce and consequently expensive resource for at least a decade, it may be more effective to spread them relatively thinly across a large number of vehicles rather than under-utilise them in a much smaller fleet of over-electrified vehicles.

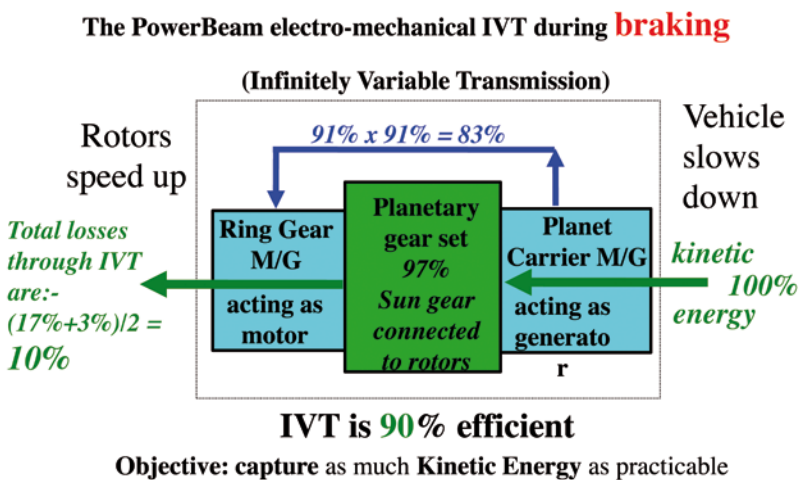

The PowerBeam electro-mechanical IVT during braking
(Infinitely Variable Transmission)
Rotors speed up
91% x 91% = 83%
Vehicle slows down
Total losses through IVT are:- (17%+3%)/2 = 10%
Ring Gear M/G
acting as motor
Planetary gear set 97%
Sun gear connected to rotors
Planet Carrier M/G
acting as generator
kinetic energy 100%
IVT is 90% efficient
Objective: capture as much Kinetic Energy as practicable

Figure 4: Power Beam electro-mechanical IVT operations during check braking

A simplistic architecture for a plug-in hybrid assumes a large, monolithic battery pack providing both sufficient AER and enough power to support strong acceleration and absorb surges of energy from regenerative braking. However, this effectively excludes the many applications worldwide for fuel-only hybrids, and the possibility of fuel cell vehicles eventually becoming commercially viable. More attractive as a foundation architecture is a combination of an SPU and a plug-in battery pack, the former optimised to deliver strong acceleration and efficient regenerative braking, while the latter provides the required number of all-electric miles in the most cost-effective manner. This modular approach also allows a manufacturer to offer a range of options which can be tailored to meet the different needs of customers.

5 Reduced Impact of Weight Reduction

The introduction of really efficient, powerful SPUs has another effect which will cause some re-thinking of development priorities. Reducing the weight of a vehicle travelling at a steady 130 km/h on a level straight road has little impact on fuel consumption, within broad limits. However, when a conventional vehicle's duty cycle requires large and frequent changes in speed, weight reduction becomes very beneficial, both in terms of accelerative performance and fuel consumption. But consider the impact that a SPU with a full-cycle regenerative braking efficiency of 60 % or better will have on the value of each kilo of weight reduction. If the SPU can also provide sufficient additional power to allow a radical reduction in engine power (and weight) then vehicle designers are able to make some interesting tradeoffs. If performance, including handling, is the dominant requirement, then both surge power and weight reduction deserve attention. However, if comfort (and perceived safety) are more important than performance and a choice has to be made between the two on cost grounds, it is likely that more of the development budget will be spent on surge power, because the benefits of weight reduction in reducing energy consumption will now be much less obvious and cost-effective.

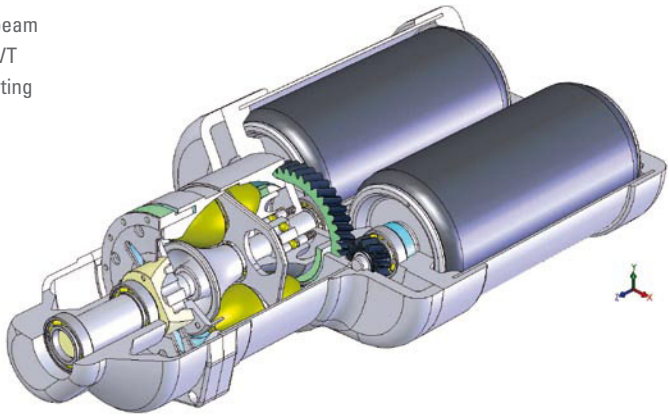


Figure 5: Powerbeam all-mechanical IVT and counter-rotating rotors

6 Tentative Conclusions

"Make cars smaller" is not going to prove as compelling or as inevitable an objective as some are predicting, but "make engines smaller" certainly will. Powerful and efficient SPUs will close the fuel consumption gap between 1500 kg and 1000 kg vehicles in the city, and the engine size gap will also close, helping to reduce the difference in fuel consumption at cruising speeds. Family cars will get lower and sleeker again, as designers pay proper attention to the impact of aerodynamics on real extra-urban fuel economy. The current fuel consumption cycles tend to mask the significant differences in fuel consumption at speed between blunt, high vehicles and those with low roofs and drag coefficients. These differences need to be exposed, by governments and the media.

Because powerful SPUs allow much more compact engines, optimum engine location may become less obvious than today. The master illustration shows a possible ultimate hybrid. To provide a low hood and roof line and a completely clean underside in pursuit of minimal aerodynamic drag, the engine is moved to the rear. Because the engine is small and light, it can be behind the axle line and under the rear trunk floor. In the illustration, a straight six is shown, its hot side to the rear, its cold side facing the passenger compartment. It can be a transverse straight six because of its small capacity. Note that weight distribution will be near optimal in this configuration, with rear engine weight balanced by the mass of the SPU behind the front axle and under the front trunk. Shown is a configuration, with twin counter-rotating rotors connected to both axles via two IVTs. However, remove the rear IVT and the propshaft linking it to the rear final drive and the car remains four-wheel-drive, but not as powerful or as expensive. Alternatively, delete the front IVT rather than the rear, and the car becomes rear-wheel-drive. Take out the battery, and the plug-in hybrid becomes a fuel-only hybrid, temporarily or permanently. On the other hand, replace the engine and fuel tank with a much larger battery and the result is a very efficient electric-only vehicle. Low-cost hybrid derivatives are also possible, with the engine integrated with the SPU.

Powerful, highly efficient SPUs will become the foundation technology for the advanced road vehicles of 2012 and beyond. The balance of power between fuel-only hybrids, plug-in hybrids, fuel cell vehicles and "pure electrics" will vary geographically and change over time, but expect to see kinetic energy SPUs in most of them.

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[1] Ellis, C.W.H.: The Future of F1 Engines. In: Racecar Engineering magazine, May 2007

[2] Patent number: GB2405129 Kinetic Energy Storage System

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